Constellation of MicroSats to Search for Near Earth Asteroids

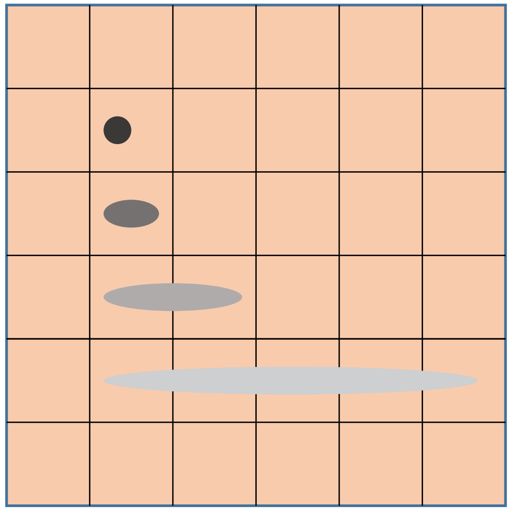
Michael Shao
Jet Propulsion Laboratory,
California Institute of Technology

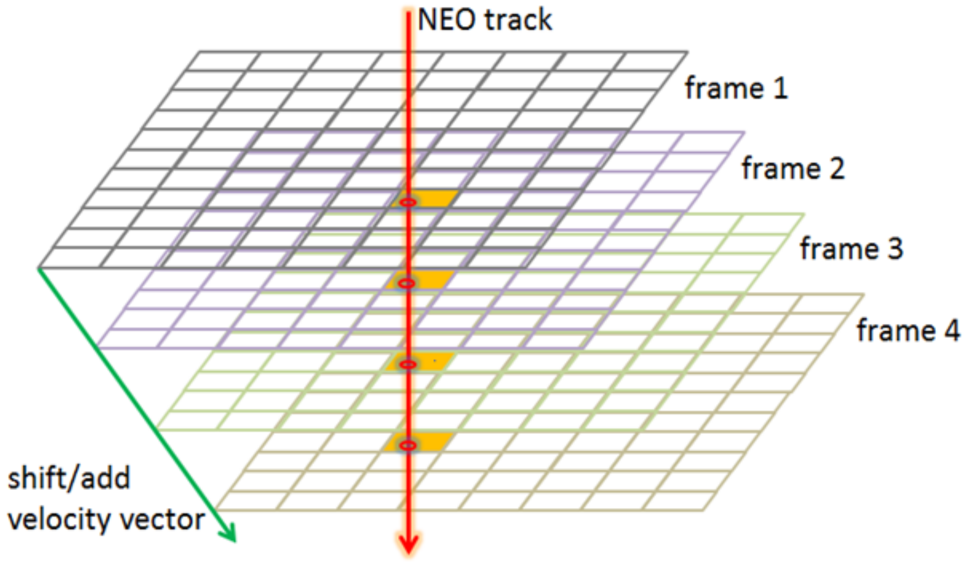
Outline

- Technique of Synthetic Tracking (ST):
  - Basic principles, enabling technologies, benefits of ST and its advantages
  - Technology advancements since our initial paper (Zhai, Shao, et al., 2014, ApJ 792, 60)
- Simulation of a NEO search relying on a constellation of 5 Microsats:
  - NEO orbit determination (cataloged detections) with Microsats using different approaches
  - Comparison with the next generation of the NEO search facilities
- The saturation effect:
  - Why a constellation of Microsats with small ~20-30 cm telescopes can dramatically outperform the next generation of planned NEO search facilities.
- Ground-based NEO searches using Synthetic Tracking
- Emerging capabilities for space-based NEO searches:
  - High cost of space missions today is from using one of a kind spacecraft ⇒ $$$
  - New generations of micro/nanosats offer huge cost savings
- Measuring diameters of NEOs:
  - In follow up mode, using Microsats with thermal IR.

Challenges in Detecting Moving Objects

- When an object is rapidly moving across a focal plane, its photons are deposited across a streak of pixels.
- The maximum SNR occurs for an integration time for which the motion $\simeq$ PSF's diameter
  - Longer exposure times do no increase the peak flux, they just increase the sky background noise.
- Synthetic tracking overcomes these challenges by taking multiple short exposures and "stacking" them with a shift/add algorithm
  - To enable this advantage, two critical technologies are needed i) Low noise high frame rate focal planes, and ii) high-performance processors.
  - Both of these technologies became available in the last several years.





Technology Requirements for Synthetic Tracking

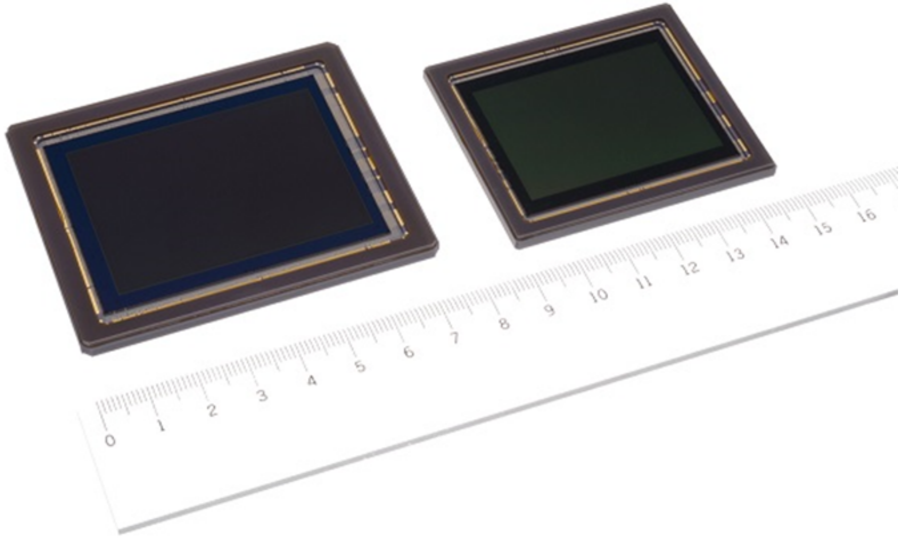
- Low noise high frame rate focal planes is the first enabling technology
  - The read noise must be below the photon noise of the zodi-sky background
  - The current generation of sCMOS detectors with ~1.5e read noise satisfies this requirement. In fact, 36 Mpix devices are now available and even larger, >100Mpix, devices will soon be available.
- With shift/add algorithm, we don't know the velocity of object before it was detected.
  - As a result, we have to "try" many velocities (as many as allowed by the targets we are trying to detect.) Typically, for NEOs we try ~10,000 velocities.
  - This is computationally expensive task that requires TFLOP class processing. The data volume is large (as we are taking video not single images) and, in many instances, it is inconvenient to transport the data from the mountain to a super computer.
  - Modern GPUs and FPGAs are now available that can provide TFLOP processing at very low cost, thus providing the second enabling technology.

Small ST Telescopes: Sensitivity & FOV

- Current ground based telescope:
  - 28 cm diameter, f/2.22, 16 Mpix CMOS sensor, low QE, FOV 2.0sqdeg / telescope
  - Observing cadence, 100 images 5 sec/each
  - Limiting magnitude of 20.8mag (21 mag/arcsec^2 sky background, 2 arcsec FWHM)
- In Dec 2017, Sony came up with a new CMOS sensor
  - 100 Mpix format, with ~1e$^-$ read noise
  - Backside-illuminated with QE of > 90%
  - Camera will become available in March 2019(?)
- Celestron has a 35 cm version of it's f/2.22 telescope

Near Future

100 Mpix & 150 Mpix CMOS backside sensors



- In Dec 2017, Sony came up with a new CMOS sensor
  - 100 Mpix format, with ~1e$^-$ read noise
  - Backside-illuminated with QE of > 90%
  - Camera will become available in March 2019(?)
- Celestron has a 35 cm version of it's f/2.22 telescope
- Assuming 2.0 arcsec seeing, 21 mag sky background, with 500 sec integration time, we have
  - Limiting mag 21.8 mag
  - FOV 7.4 sqdeg (per telescope)
- In space (22 mag sky) 28 cm telescope
  - Limiting mag 22.56 mag (500 sec)
  - 12 sqdeg FOV (100Mpix 11656*8742)
  - (cover ~ 15,000 sqdeg in 8 days)

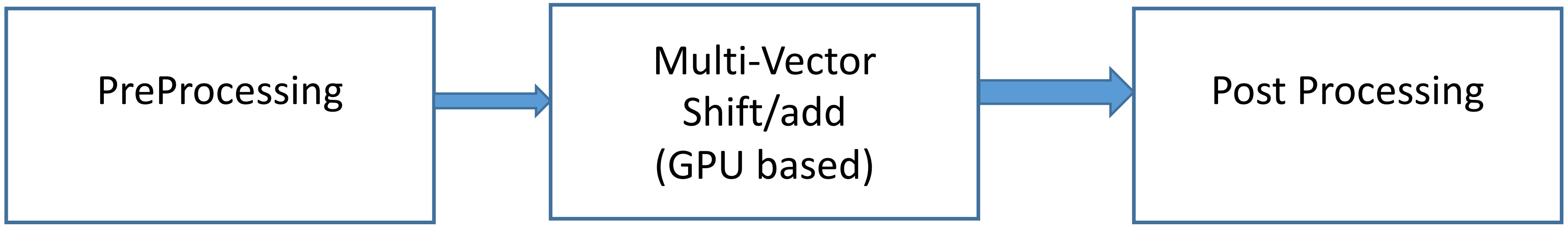
- In our (2014) paper on a constellation of Cubesats, we had a 5 Mpix CMOS camera; there were no backside CMOS sensors.
- We hypothesized that in a couple of years a 16 Mpix sensor would be available and further in the future 8K or 64 Mpix sensor.
- Reality is even more exciting: In 2018, Sony came up with a 150 Mpix backside sensor.

Advantages of ST

- Allows small telescopes to have the same sensitivity as much larger telescopes.
  - Ground based 21.8 mag & 7.4 sqdeg with 35cm telescope. (500 sec tracklet)
  - Multiple small telescopes with similar sensitivity and sqdeg/8hr sky coverage but for < 1/10 the cost.
  - For NEOs smaller than H=22mag ST advantage is greater. (a single 35 cm ST telescope 100Mpix, equiv to ~2m 7sqdeg at for ~90m or smaller NEOs.
- The same applies to small satellites in space, but in space one can avoid saturation with widely spaced telescopes.

Outline of Syn Tracking Video Processing

- Basic data set ~100 images taken at 0.2Hz (much faster of earth orb objects)
- Processing on a ~4 GPU (56TF peak) cluster in real time (GPU box can hold 8 GPUs)
  - 500 s data collect, ~ 200s analysis latency



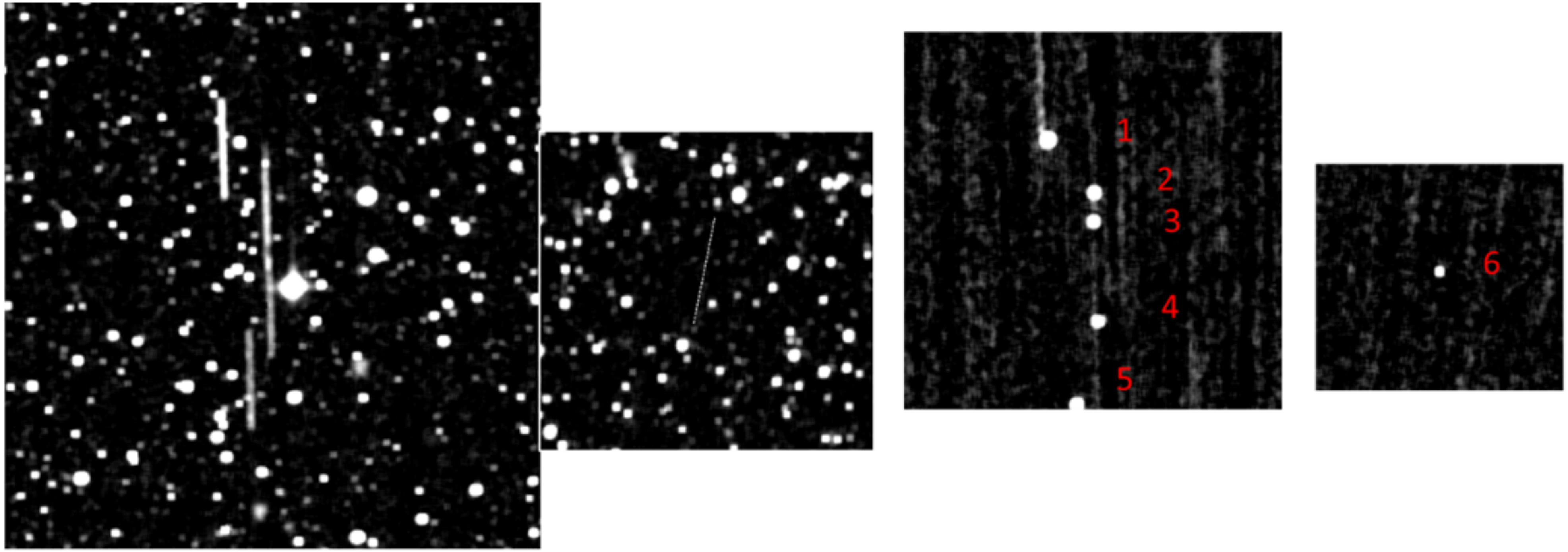
- Dark/sky subtract
- Flat field correct
- Cosmic Ray removal
- Register stars/ remove stars.
- Apply bad pixel map
- Convolve with matched kernel

- Currently search 100*100 velocity Space

- 3.5K*4.6K image
- (11K*9K image with 100Mpix sensor)

- Perform NLLS fit for each detected object found in MVSA operation
- Star matching against GAIA-2
- Astrometry/photometry calibration using 100~200 GAIA stars
- 7 sigma detection threshold

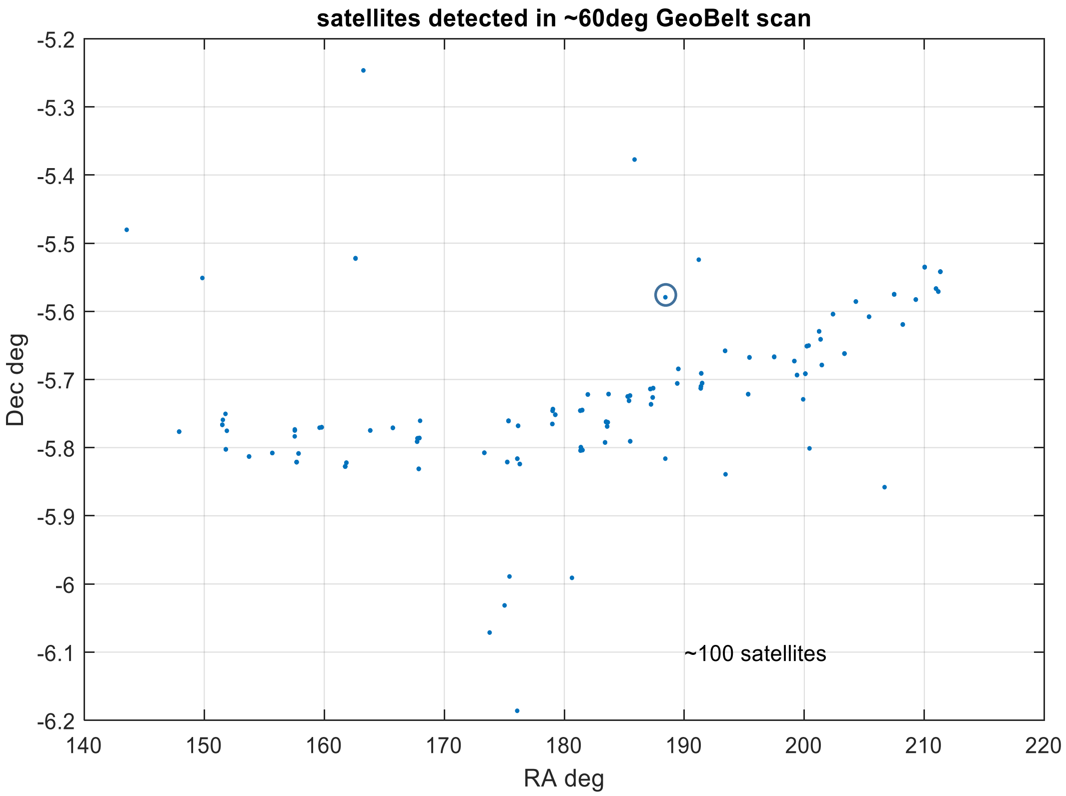
Detect Multiple Objects at Different velocities

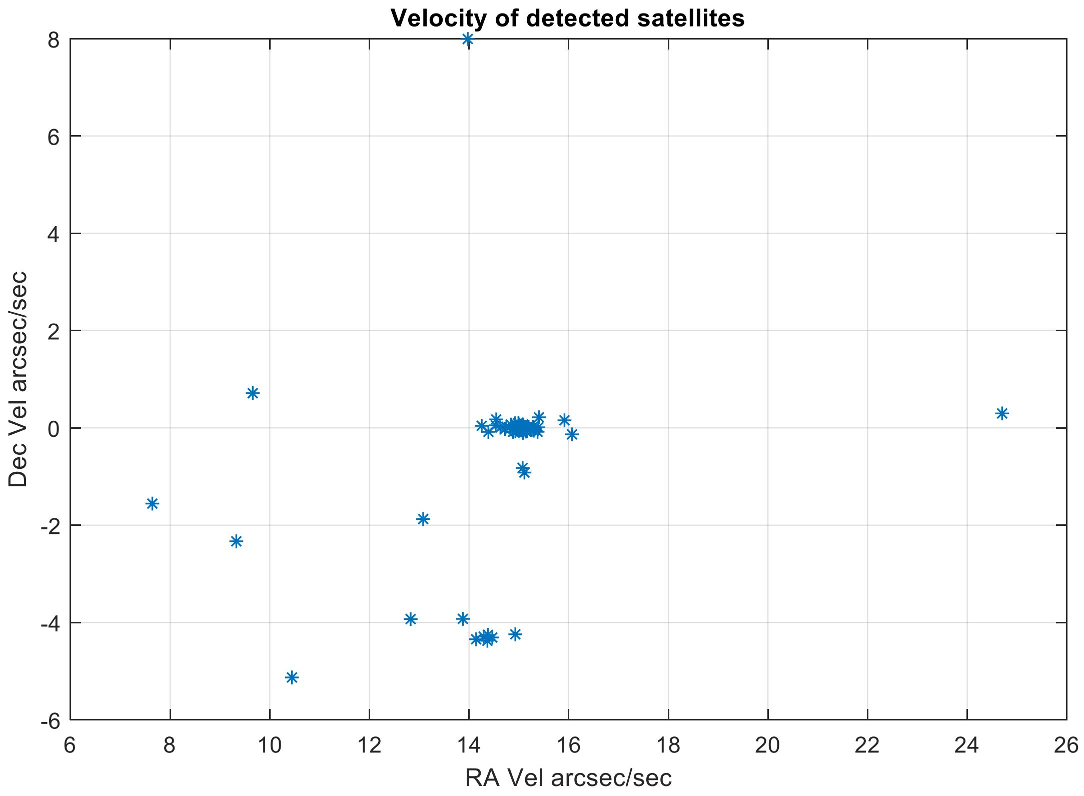


- The streaks here represent 5 objects moving at the same velocity. RA direction is up/down.
- The 6th object is not detectable in the sidereal image, the dotted line (2-nd figure) shows where the streak would be if it were bright enough to be seen. The far right image is using synthetic tracking at the object's velocity (inclined orbit).
- The average flux for object 6 was 1.1 photons/frame (240 frames co-added).

Detecting Large Numbers of Earth Orbiting Objects

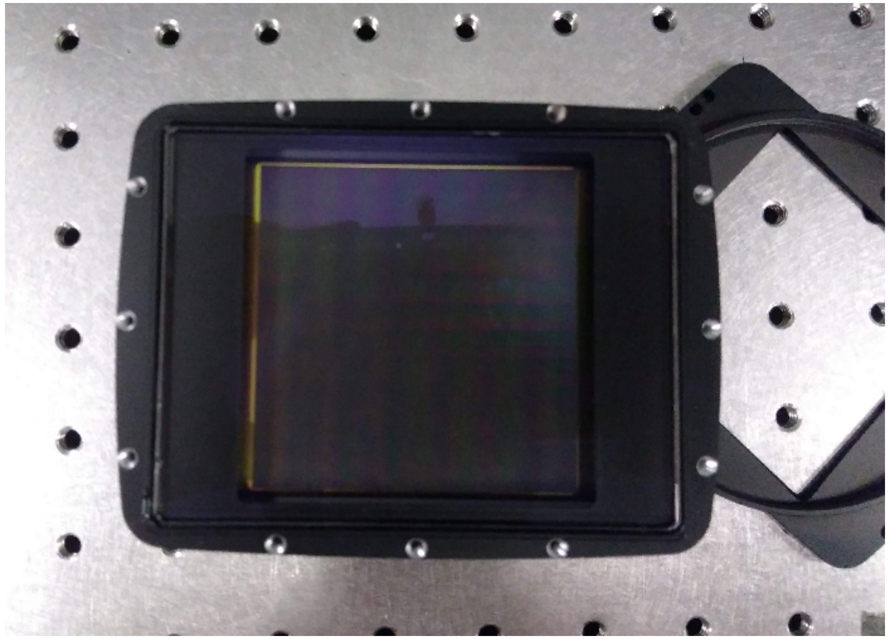
- Synthetic tracking's advantage increases with the angular velocity of the object. This offers a very significant advantage for Earth orbiting objects.





Current Activities

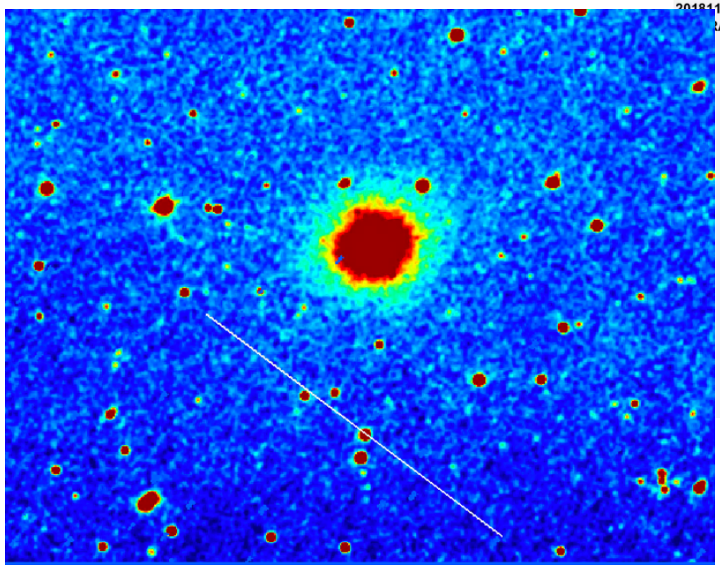
- Large format CMOS imager
  - Raw data volume 22 Terabyte/8hr night
  - Real time data analysis
  - ~60 Teraflop peak throughput
- Test software on small telescopes at a dark site, before testing on customer's facility. on sky tests:
  - Sensitivity,
  - Astrometric accuracy,
  - Keeping up with real time analysis
  - False positive/false negative testing
    - Robust, no human in the loop operation
  - Operation under non-ideal conditions (thin clouds and moon)
  - Operational strategy (follow up, initial orbit det.)
- Current system is a prototype of what will be an operational SSA system.

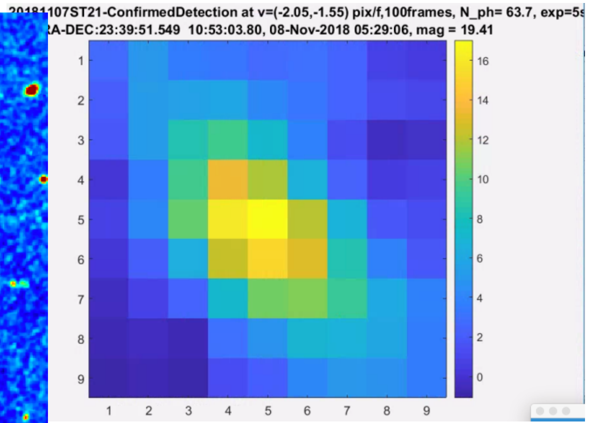


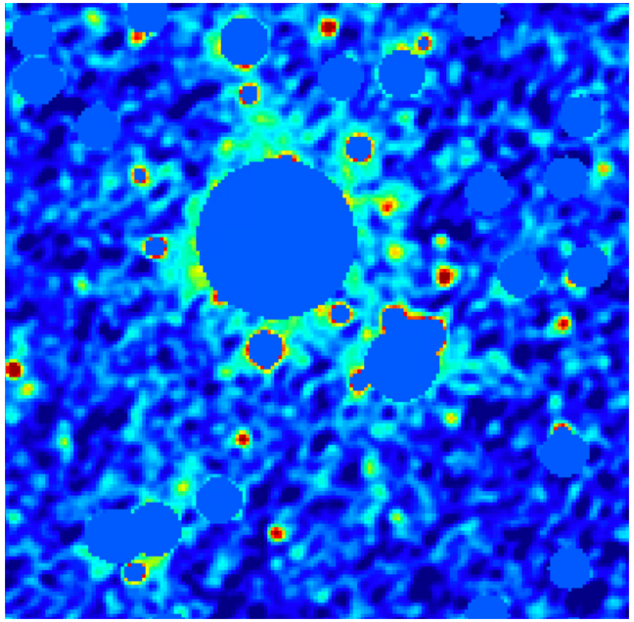
Video frame rate ~50-100X higher for SSA than for NEOs

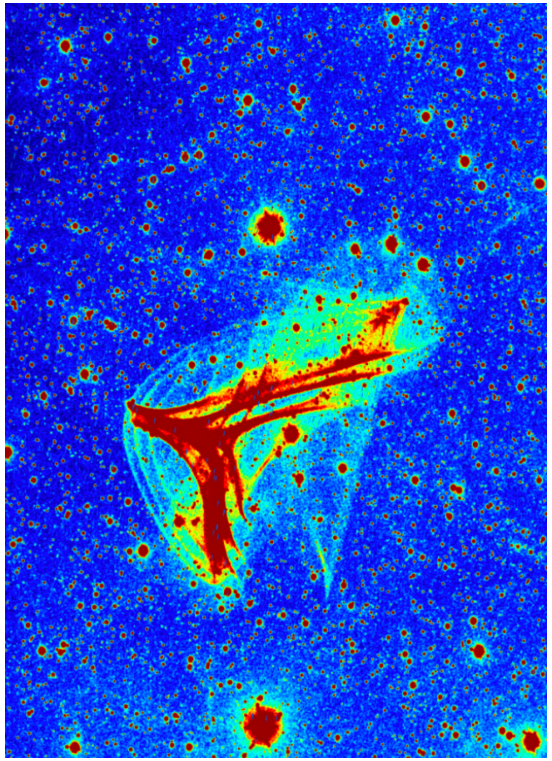
Important to have on sky data to test data processing pipeline

- Synthetic tracking is immune to many sources of false positives (a object has to move linearly in time) in the same way a 4 image tracklet is immune
  - Track of NEO runs over one or more stars
  - Astronomical objects with nebulosity
  - Wing of bright stars, not removed will increase noise if NEO track goes through that area



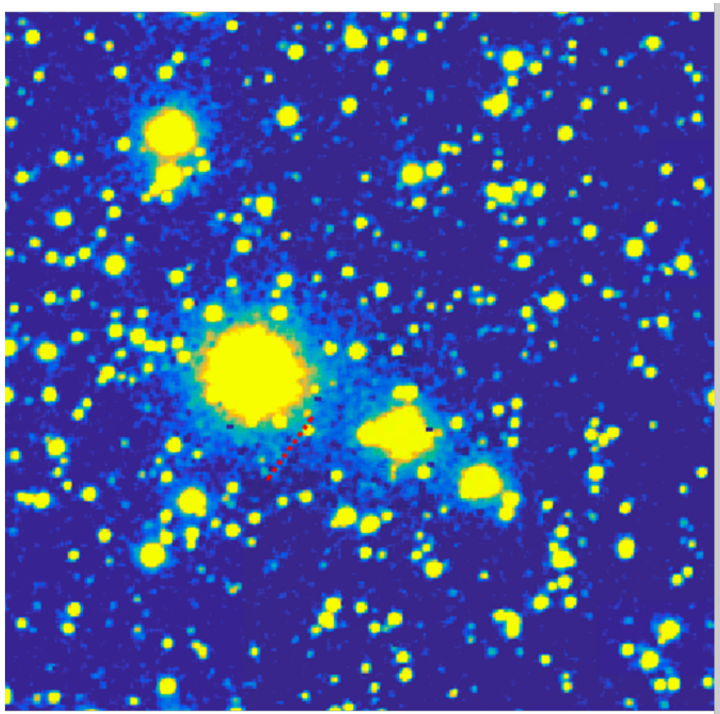


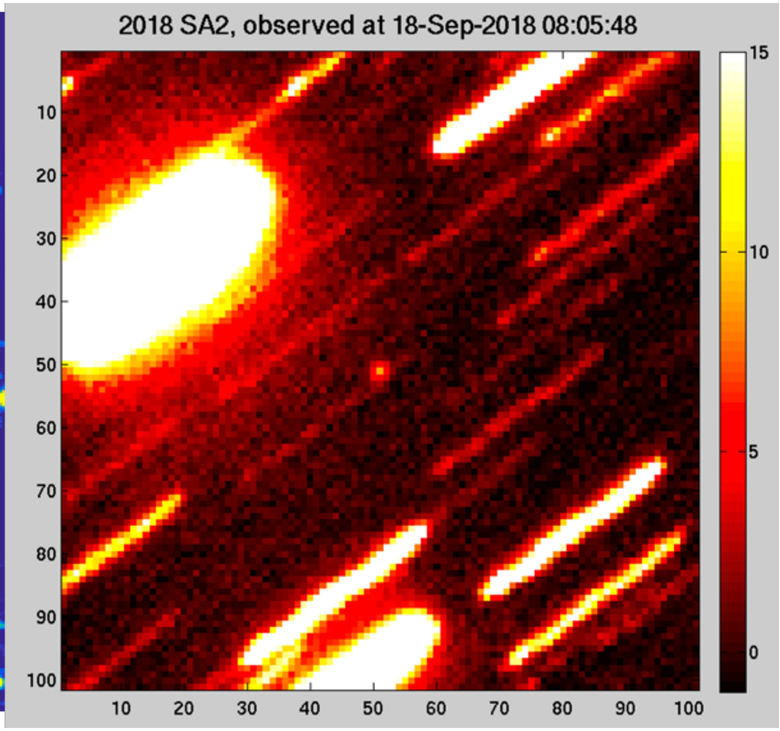




Synthetic tracking: sensitivity

- Data from 28 cm telescope with 16Mpix and 35% QE sensor
- Detection threshold at SNR~7 implies limiting mag 20.34
- Improved telescope focus (2.7 arcsec FWHM to 2.0 arcsec FWHM) and 500 sec vs 400 sec ~20.8 mag limit





- 1st detection of 2018 SA2 on Sep 18, 2018: 19 mag, 400 sec (using 80 of 5 sec images) at SNR of ~24
- Observed twice (1hr apart) on 2 nights.
- After our initial detection other observatories followed up with a dozen of confirmed detections.

Astrometry of Streaked Images

Stationary target on sky

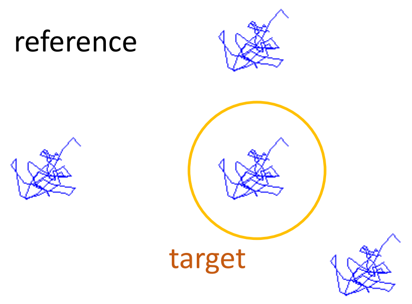


Image motion caused by telescope pointing and atmospheric turbulence is mostly **common mode**, and drop out, for "relative" astrometry

Moving target on sky

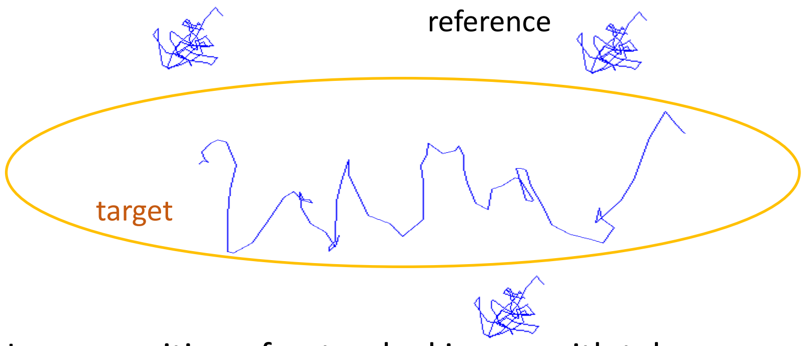


Image position of a streaked image with telescope or atmospheric jitter:
astrometric errors are *no longer common mode*

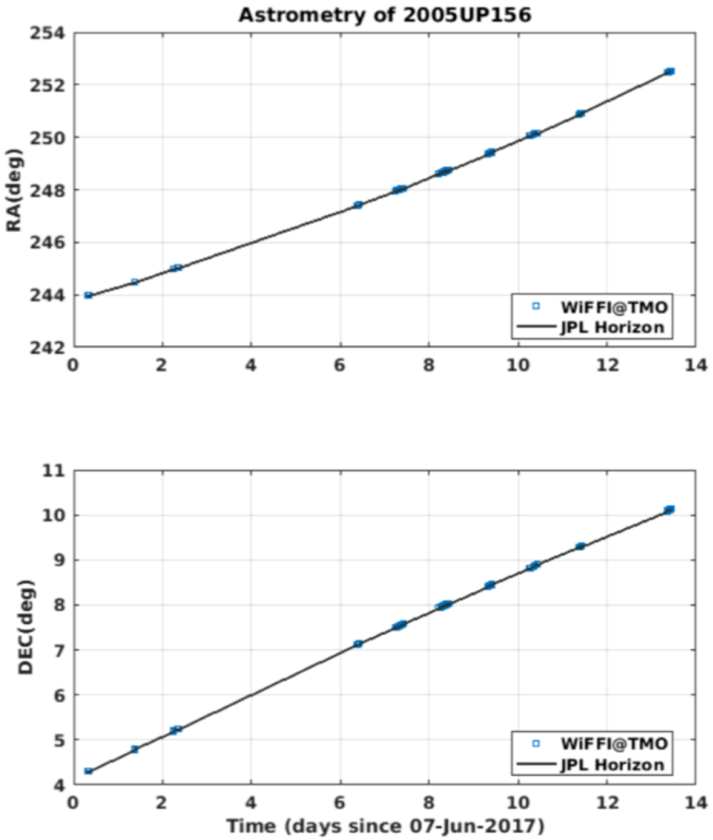
P. Vereš et al. / Icarus 296 (2017) 139–149

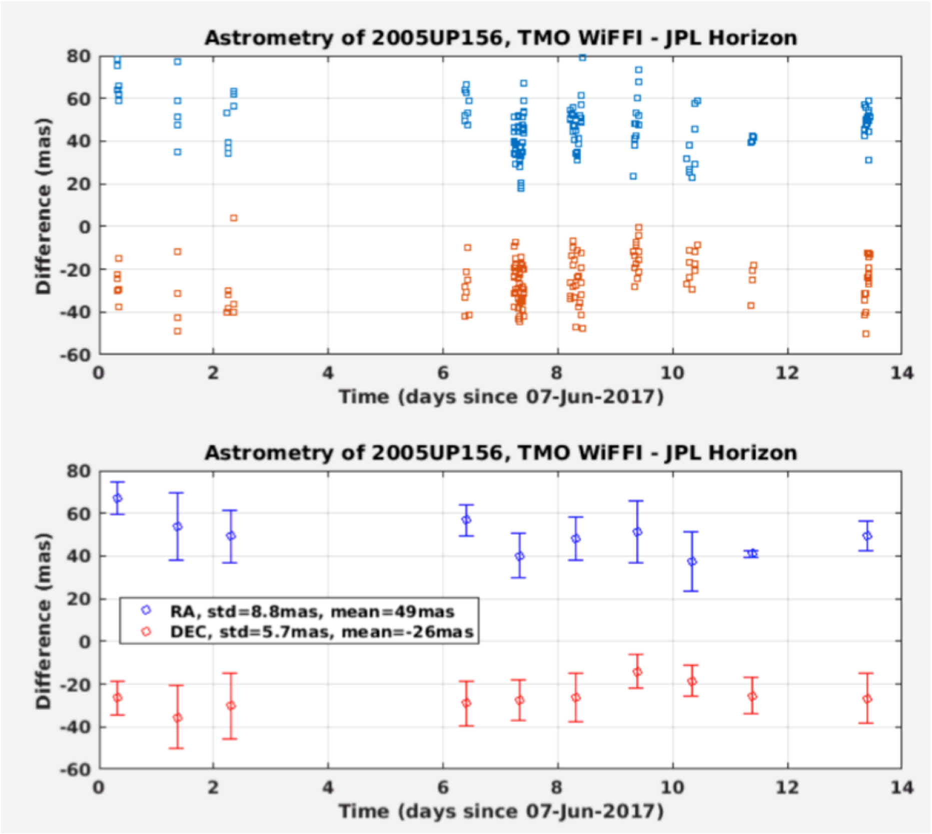
Table 1
The most productive asteroid surveys are listed with the RMS of their astrometric residuals for multi-apparition asteroids. Statistics for all detections and the fraction of observed known asteroids is current as of February 9, 2016.

N	Station Name	MPC Code	RA RMS	DEC RMS	Detections	Asteroids	Fraction of Asteroids
1	LINEAR	704	0.67″	0.66″	32,777,288	370,033	53%
2	Mt. Lemmon	G96	0.31″	0.28″	18,640,225	619,386	88%
3	Pan-STARRS1	F51	0.12″	0.12″	18,400,219	616,209	88%
4	Catalina	703	0.69″	0.67″	17,802,653	436,810	62%
5	Spacewatch	691	0.37″	0.34″	11,719,895	566,880	81%
6	SST	G45	0.36″	0.36″	9,915,512	300,495	43%
7	LONEOS	699	0.65″	0.59″	5,367,447	261,585	37%
8	NEAT	644	0.30″	0.36″	3,926,121	302,846	43%
9	Purple Mountain	D29	0.50″	0.47″	3,214,197	274,301	39%
10	WISE	C51	0.55″	0.59″	2,222,396	149,884	21%
11	Siding Spring	E12	0.49″	0.52″	2,228,965	168,462	24%
12	Haleakala-AMOS	608	0.72″	0.85″	1,286,280	144,827	21%
13	La Sagra	J75	0.42″	0.39″	1,159,632	153,233	22%

- The astrometric accuracy of NEO search telescope vary. The best seems to be Pan-STARRS with ~120 mas (milliarcsec) rms residuals.
- NEO search cameras have large FOV, and often large pixel sizes (in arcsec). Also, pixilation noise could be the reason why some observatories have 500 mas or larger errors.

Synthetic Tracking Astrometry (streaks removed)



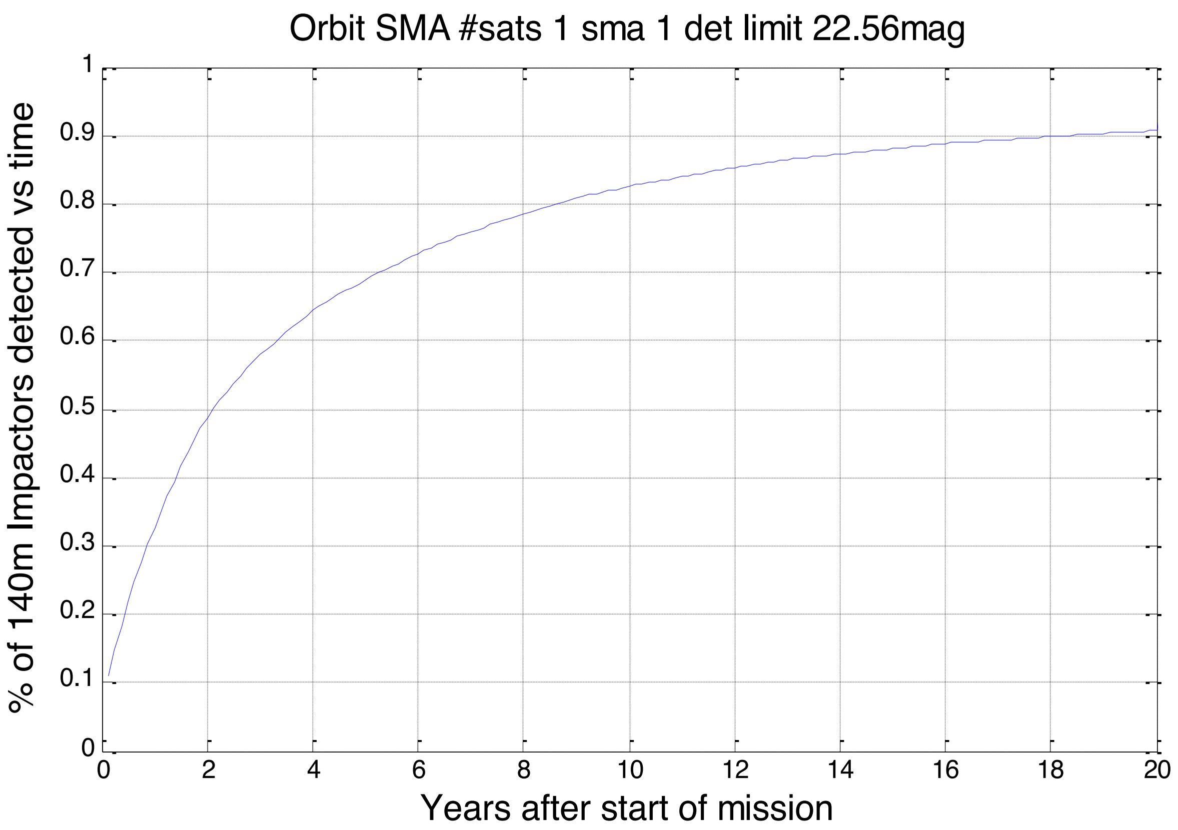


Zhai, et al. ApJ, 156:65 (2018)

441 observations of 12 known NEOs in 2017

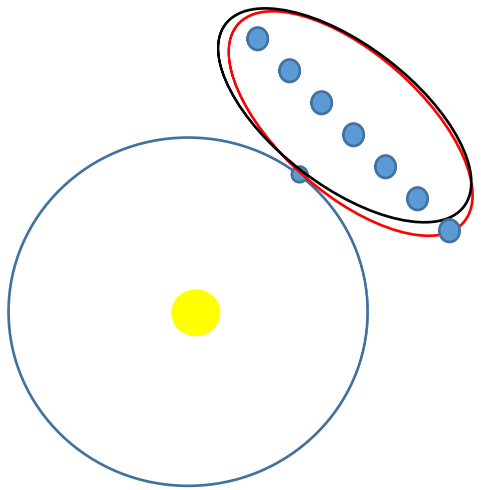
- Known NEO 2005UP156 observed multiple times over 2 weeks.
- Offset between our measurements and the ephemeris from Horizons is ~40 mas.
- Scatter of our measurements over this 2-weeks data set is **6 mas** in dec, **9 mas** in RA.
- ~440 measurements of known NEOs (2017-18) average to ~20-30 mas.

NEO Search Simulations



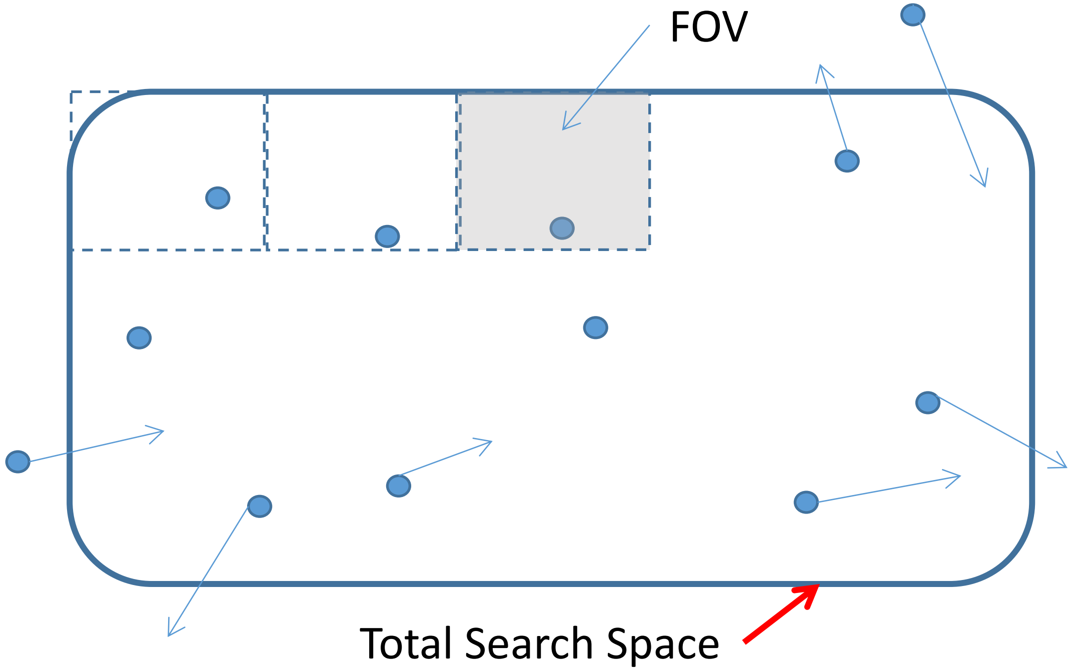
Single Microsat 28cm 100Mpx 22.56 mag/500 sed 12sqdeg

- Cumulative detection of unique NEOs vs time. There are three regimes:
  - Beginning (start from zero);
  - Intermediate waiting for the sky to change;
  - End (near 90%) waiting for long period NEOs.
- Among the other effects, the most important one is saturation



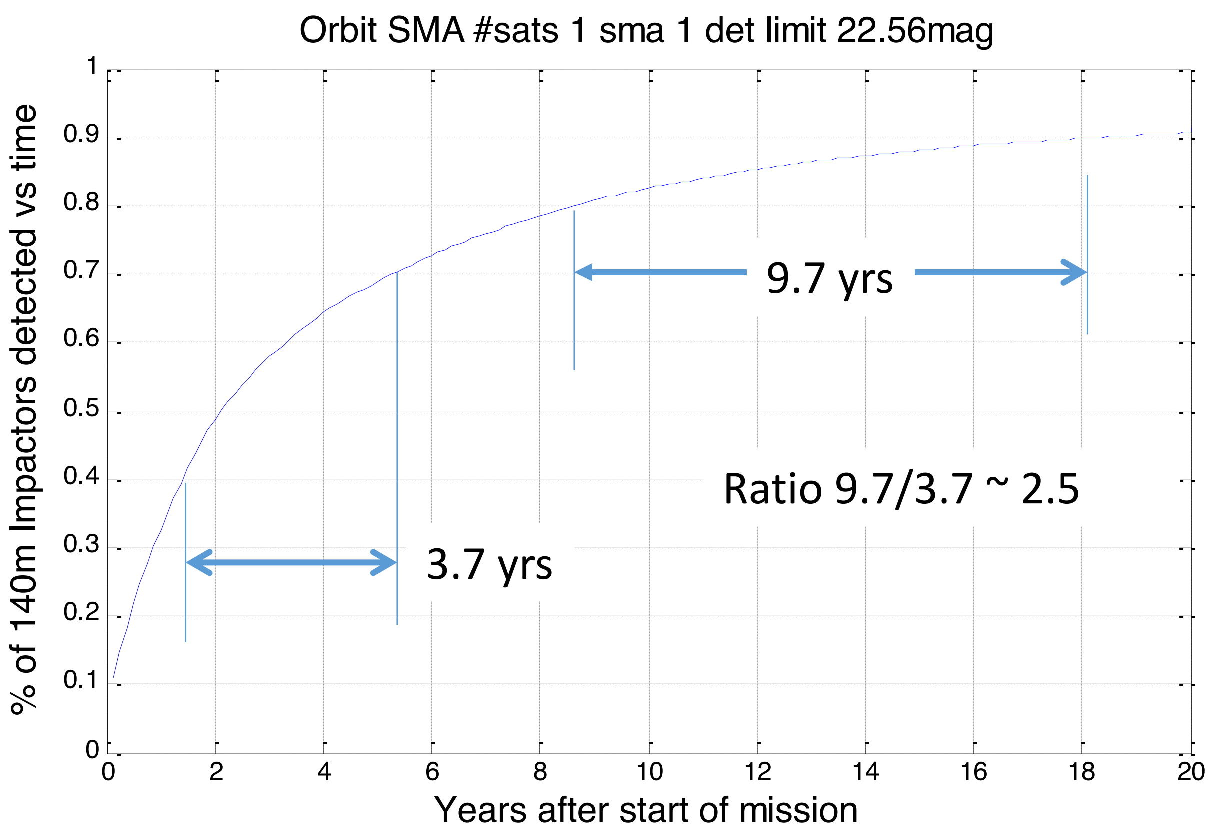
Startup (from zero or from N% already found)

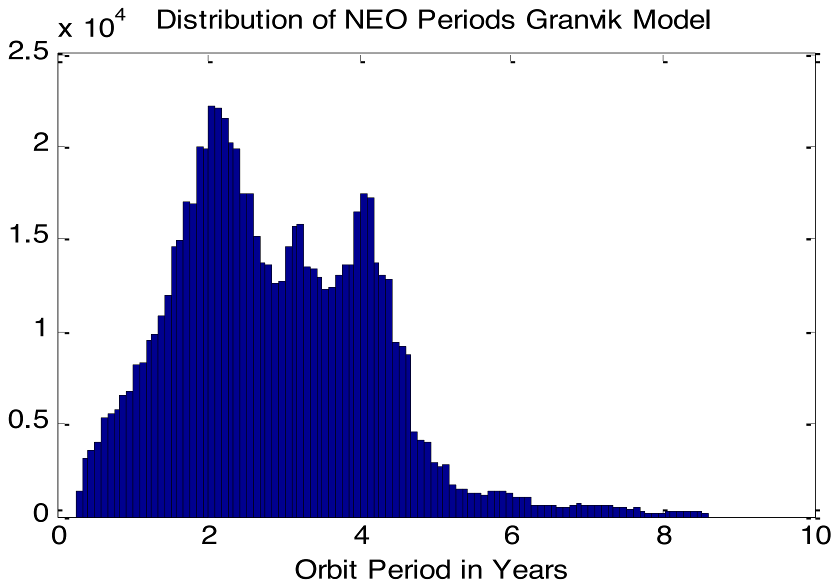
- The 1st time a new (more sensitive) telescope scans the sky for NEOs, it will detect many objects in the search space, that are detected for the 1st time.
- But after scanning the search space once, the 2nd scan will mostly detect objects that were detected in the 1st scan. A few objects will have moved out, a few new ones will have moved in.

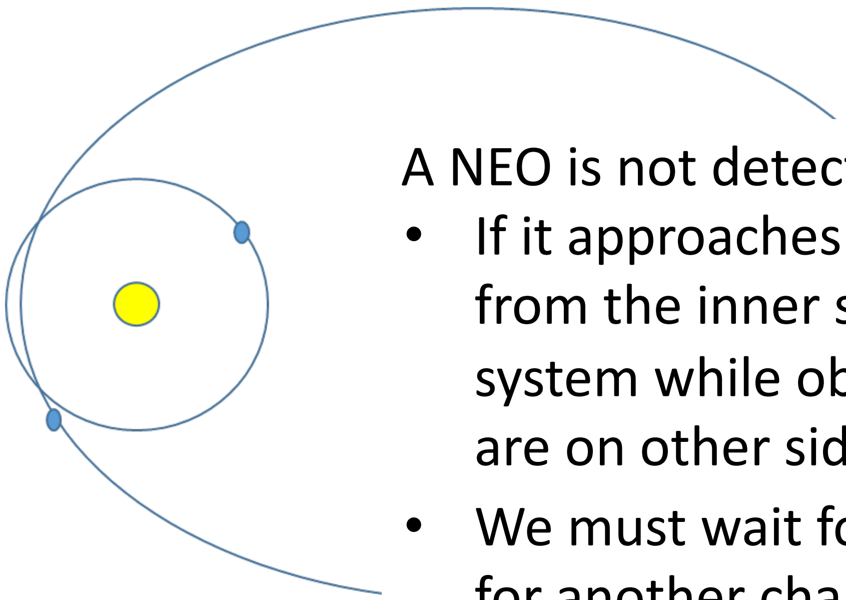


- Search out to 0.3 AU (10 km/s ⇒ ~1 deg/day). It could stay in the search space for ~3 months.
- With larger % of NEOs found, the number of new NEOs entering the search space will decrease.

Getting to 90% Complete







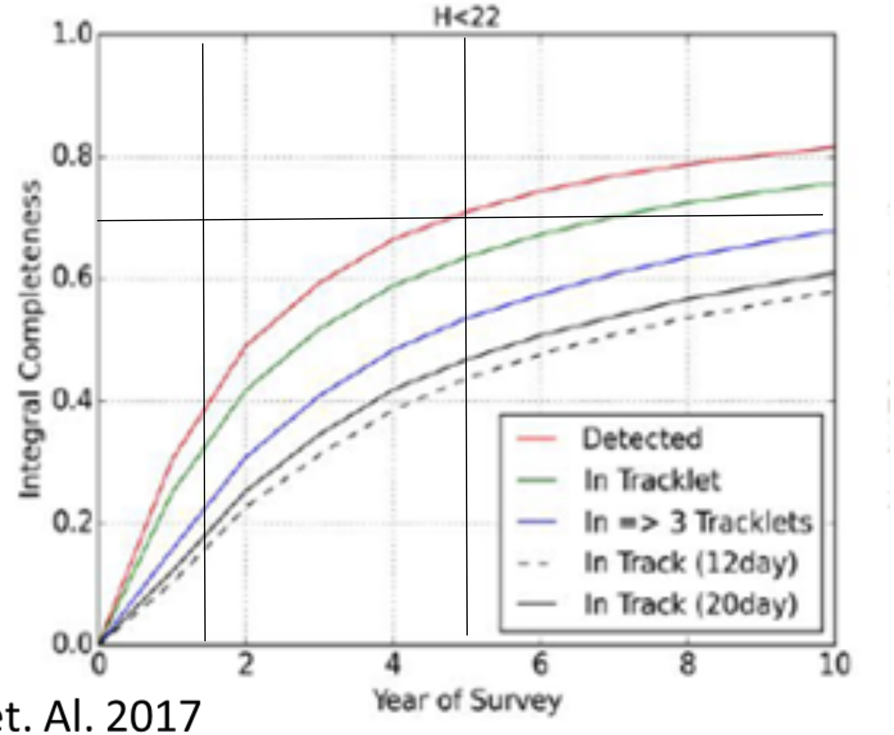
- Here, going from 40% to 70% takes 3.75 years, but going from 80% to 90% take 9.7 years
- Duration of 9.7 years comes from the fact that long-period NEOs (21% of total # of NEOs) have 4 yr periods or longer.

A NEO is not detected:

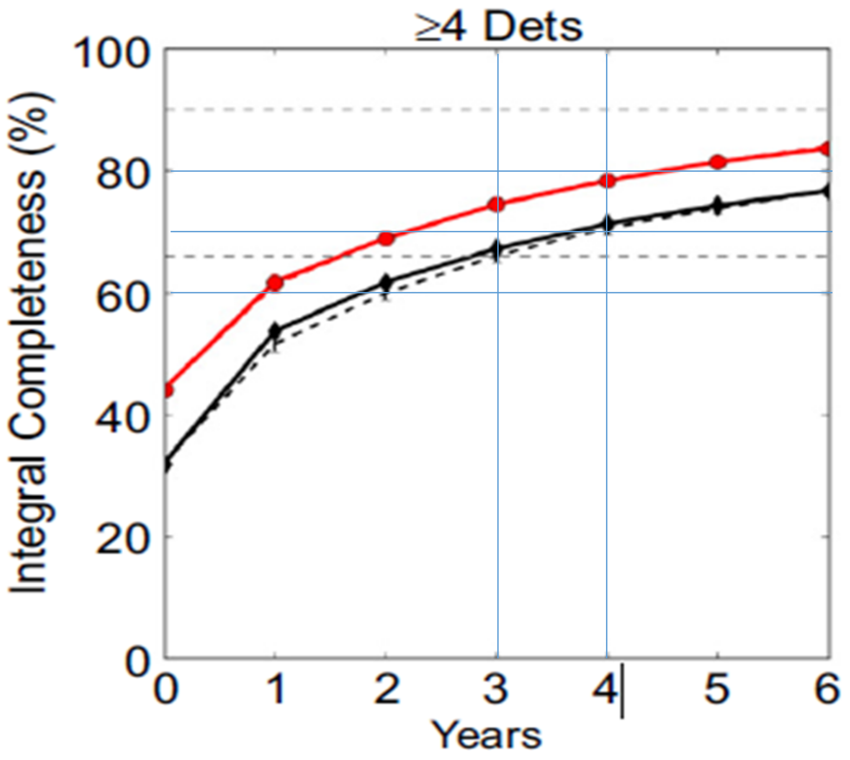
- If it approaches the Earth from the inner solar system while observations are on other side of Sun;
- We must wait for ~4 years for another chance.

Crude comparison 40-70% time

- Time to search for ~40-70% of NEOs from the NEOCam paper (Mainzer et al. 2015)
- For LSST the 40-70% time ~3.2 yrs
- Single Microsat (28 cm telescope) the 40-70% time is ~3.7 yrs



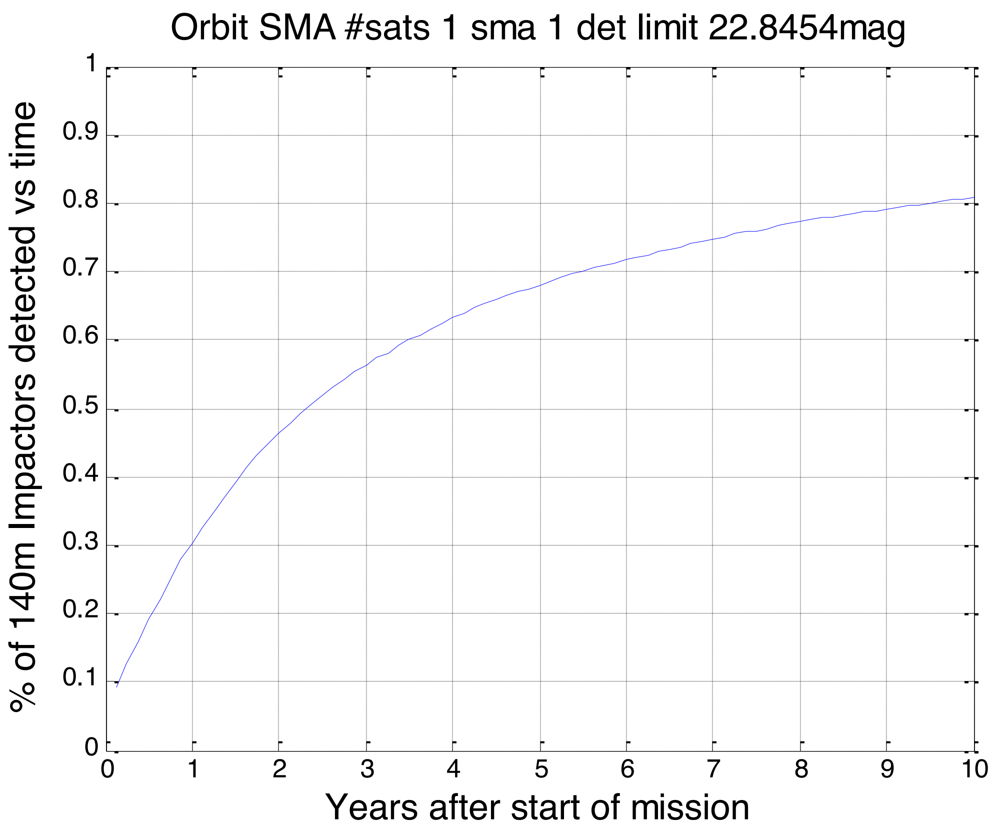
Chesley et. Al. 2017

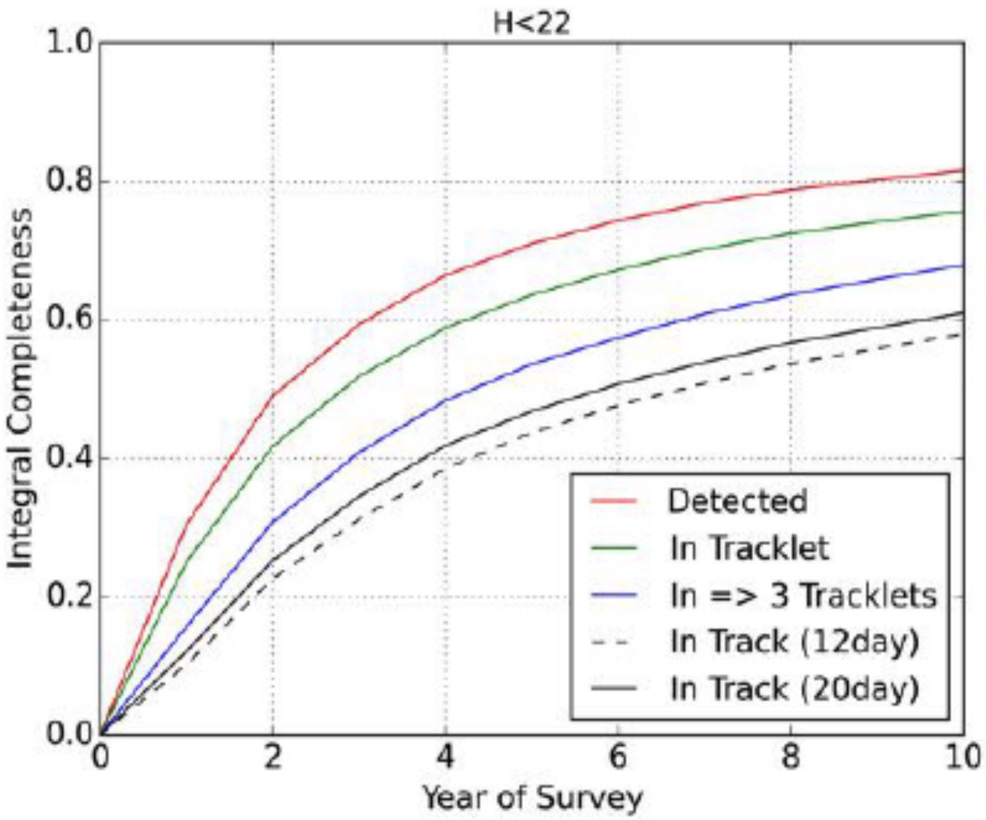


THE ASTRONOMICAL JOURNAL, 149:172 (17pp), 2015 May

Simulations of Saturation (baseline facility)

- We constructed a medium sized space telescope whose discovery performance was roughly the same as LSST (show below). It had 81% completeness for single detections @10yrs (similar to the Chesley LSST simulation)





Saturation Numerical Experiments

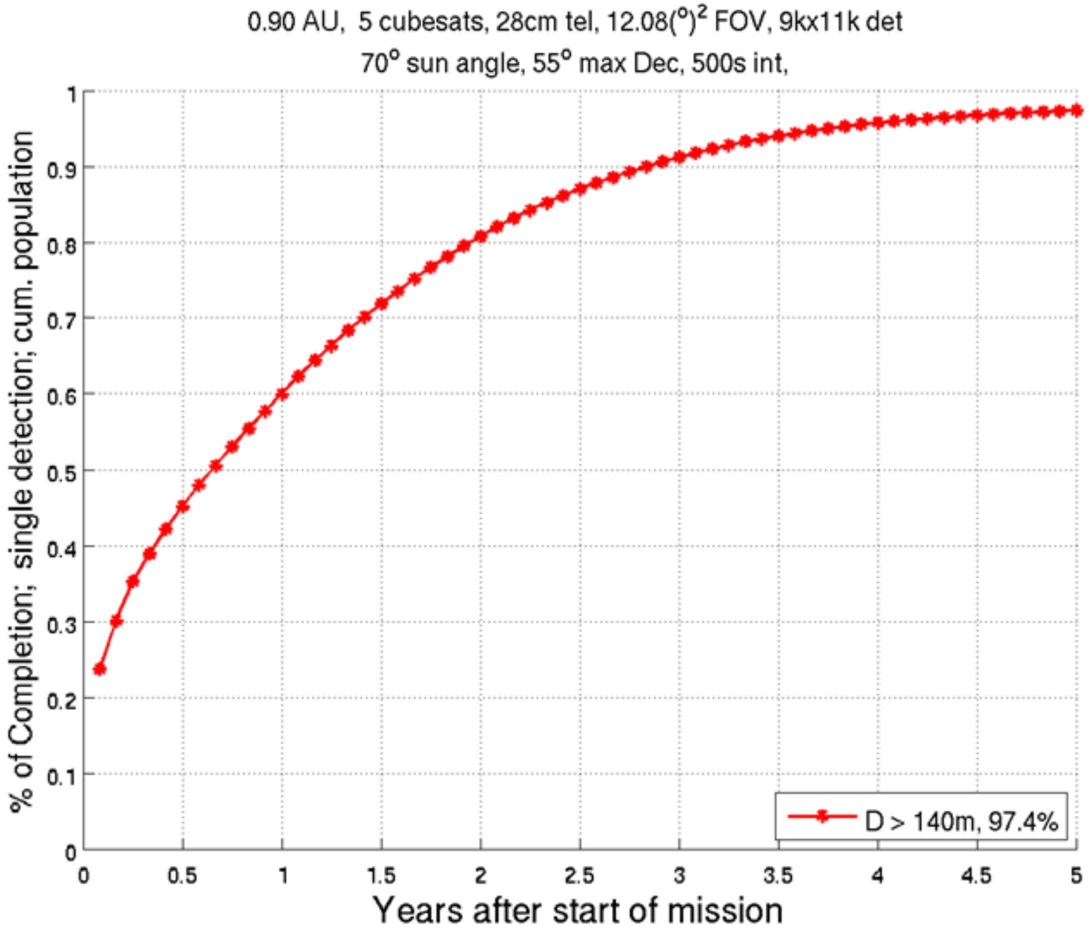
- Add a 2nd telescope at the same location
- Add a 2nd telescope in the other hemisphere (originally was limited to -70^0 to $+30^0$)
- Replace with a telescope with ½ the FOV
- Add a 2nd telescope on the other side of the Sun

Case	% complete in 10yr	
One LSST "like" facility	80.9%	-70 to +30 deg lat coverage
Two telescopes nearby	81.5%	-70 to +30 lat coverage
Two in diff hemispheres	83.0%	-70 to +70 lat coverage
1 telescope ½ FOV or time	79.2%	-70 to +30
Two opposite sides of sun	92.9%	-70 to +70 latitude

Constellation of MicroSats (nominal 5 microsats)

- **Single** Detection Completeness
- Spacecraft @ 0.9 AU from Sun
- 70^0 Sun avoid, +/- 55^0 lat
- Natural repeat cycle 9 days

- 90% complete in 2.8 years
- 40-70% complete in 1.1 years
- 97.1% complete in 5 years

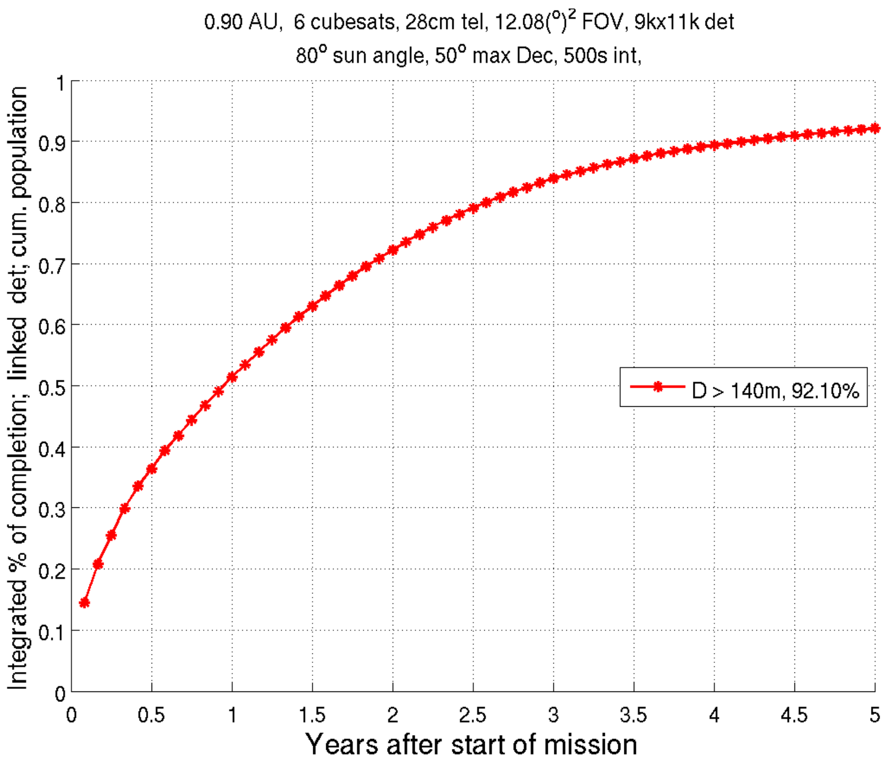


Definition of Terms (as I understand them)

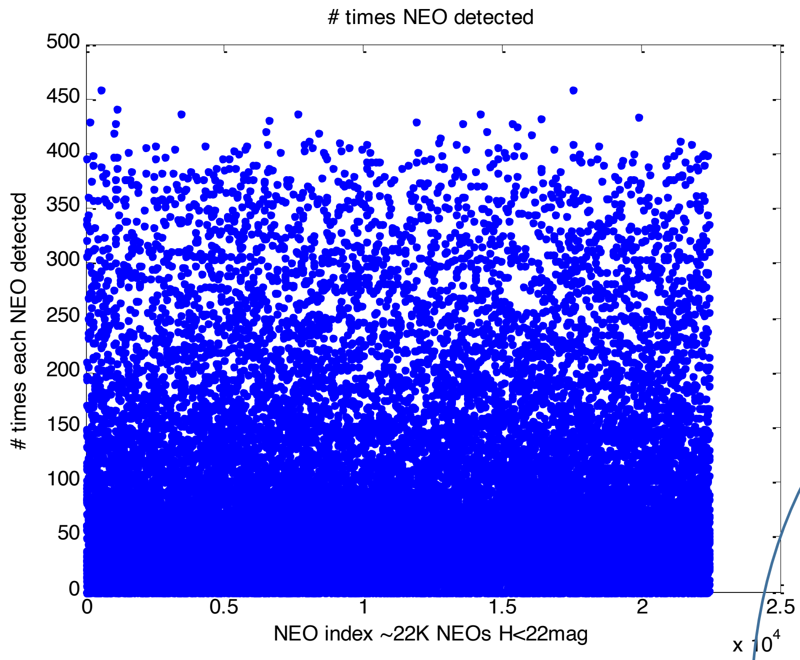
- Detect a NEO:
  - A tracklet (for syn tracking, position and velocity over a 500sec obs)
  - (or a 4 image tracklet (~30min))
- Cataloged observation:
  - At least 3 tracklets over ~18 days
- Precise orbit:
  - Multiple observations spaning > ½ orbit

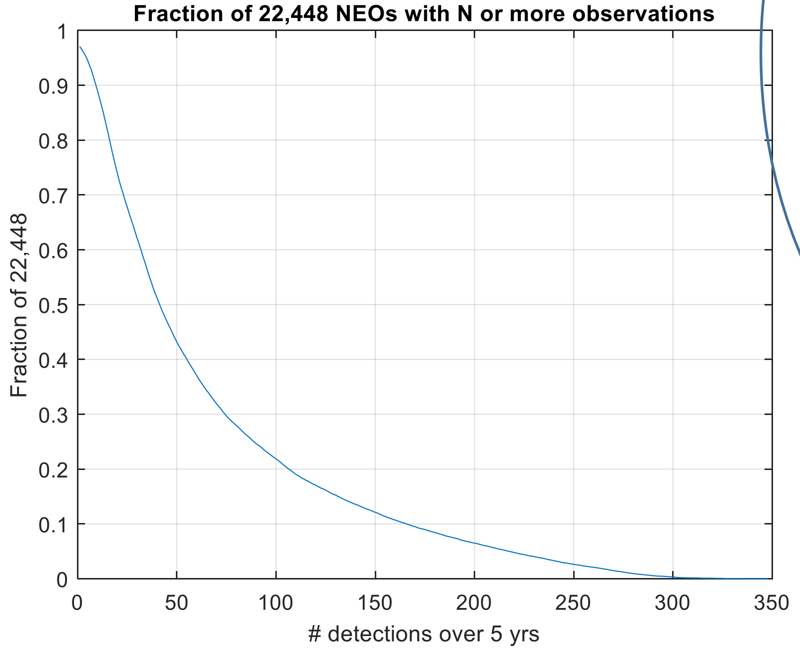
18 day tracks (with 6 MicroSats)

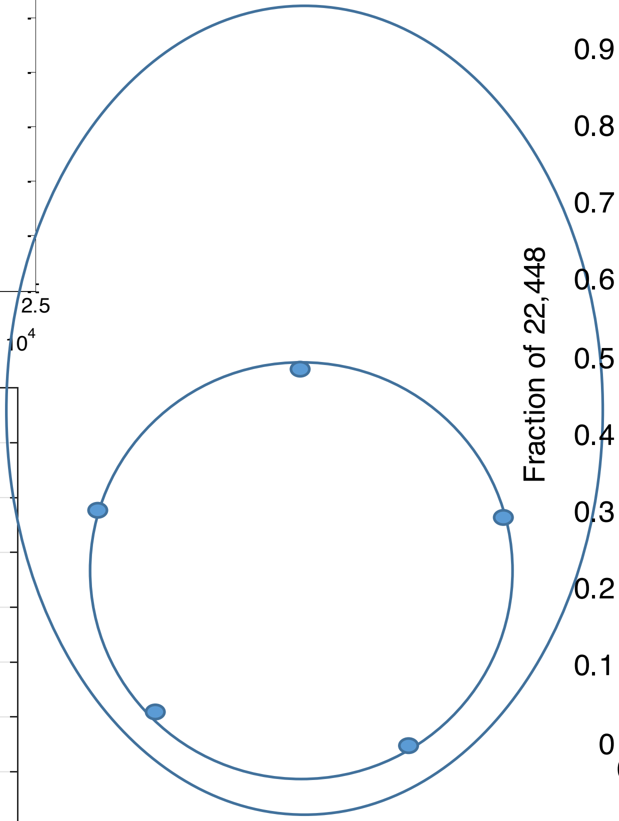
- We call a cataloged/linked detection **3 or more tracklets** within ~18 days (each with position and velocity.)
- 18 day tracks
    - 90% complete in 4 yrs;
    - Single tracklet 90% complete in 2.5yrs

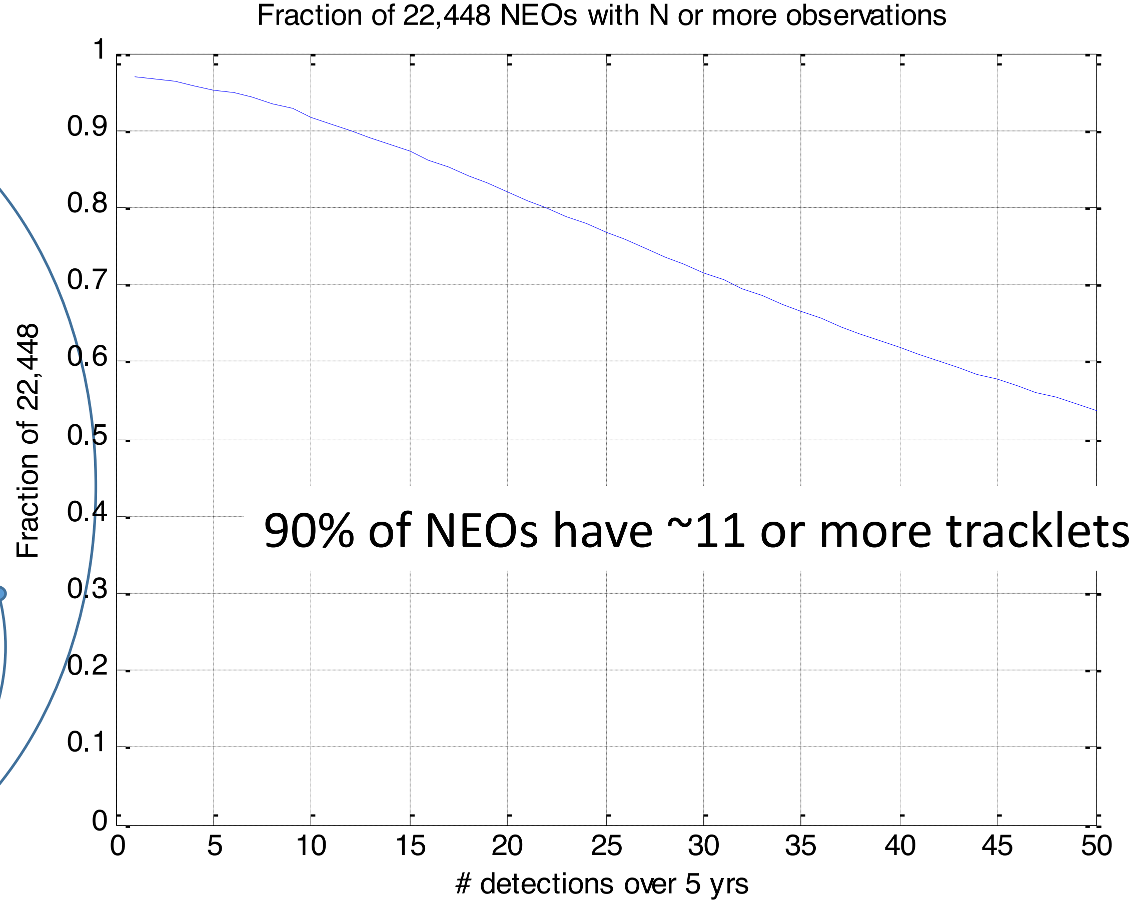


Do NEOs get detected enough times to get an orbit in 5 yrs observation?









90% of NEOs have ~11 or more tracklets

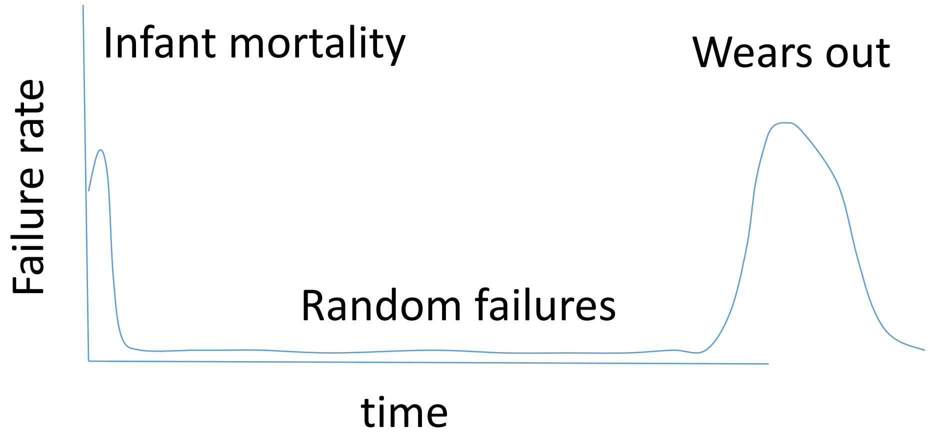
detections for each of ~22,000 NEOs with H < 22 mag

Revolution in Nanosat/Microsats
1 of a kind 1st of a kind versus Mass production

- NASA has traditionally built large 1 of a kind, 1st of a kind spacecraft.
- Medium/large NASA missions (WFIRST 2.5Billion) typically have a 5 year science design lifetime (a 10 yr design lifetime is usually considered too expensive):
  - In a class B mission what does 5 years mean? (Will it die after 5 yrs?)
  - For every critical subsystem (where failure would kill the mission) the probability that the hardware will function for 5 yrs has to be > 99.5% and there is a spare. There may be 20 critical subsystems, so this is not as much overkill as one might think.
- Most of the time a mission designed for 5yr science mission will function properly much longer than 5 years:
  - However, if you have a bit of bad luck (Kepler lost 2 reaction wheels after ~4.5 yrs) the primary mission might only last 5 yrs.

Can Microsats have 5 yr or longer lifetime?

- Devices that wear out in 10 yrs are avoided in space hardware.
- Infant mortality can be tested/screened.
- Random failure rate implies
  - Testing 1000 devices for 1 year is the same as testing 100 devices for 10yrs
- This is a common assumption when testing lifetime for space components/subsystems.



- How to you test for 99.5% for 5 years?
- You buy 1,000 devices, test for 5 years and watch < 5 fail (or 200 devices and watch 0 or 1 fail.)
- In the 2000's I was a Project Scientist for the SIM Proj and that was what we did for the high stability laser source for the laser metrology system.

How Unlucky was Kepler?

- Normal flight rules for class B missions was that the 3 reaction wheels should have a >99.5% probability of working for 5 years and there'd be a spare.
- The probability that 2 would fail in 4.5 years is ~ 4e-5
- Major spacecraft subsystems are too expensive to buy in quantity 100's. One relies on historical lifetime data
  - One reason why it's so hard to introduce new technology into space. New technology => zero historical data.
  - However, the historical data can become invalid if the production engineers/technicians retire and the replacements don't have as much experience.
- Was Kepler unlucky to the tune of 4e-5 or were they unlucky because the historical data didn't actually apply to the wheels they flew?

Microsat from Cubesat Companies   ESPA class satellite

Class	Up to 250 kg
Available Payload Volume	45 x 45 x 80 cm
Pointing Accuracy	±0.002° (1-sigma), 3 axes, 2 Trackers
Energy Storage	300Whr
Solar Panels	400W
Mass / Volume for Avionics	25 kg / 40 cm x 40 cm x 20 cm
XACT-Bus Nominal Power	< 10 W (Excluding RF Comm)
Orbit Altitude / Orbit Lifetime	LEO and GEO / > 5 years

3 ESPA missions
Under contract

Components are all off the shelf Cubesat components

Communicatioon at
X band with 20 mbit/s

Rms pointing jitter 2 arcsec rms/ 1as/s
Improve to <0.25 arcsec with
Fine guidance star tracker

S5 mission to launch not earlier than Feb 21 2019

As demonstrated with Asteria Cubesat mission
and upcoming DeMi mission (from MIT)

How Can Cubesat Subsystems Claim 5 year lifetime?

- Many 100’s of cubesats have been launched into orbit:
  - As many as 100 at a time.
- For reaction wheels, the component that failed on Kepler, BCT has 150 reaction wheels currently in orbit.
- Very low cost cubesats (< 1M for the whole satellite) are “single string”. Failure of any 1 of N critical subsystems means end of mission. (why many cubesats
- But with Cubesat components, the cost of flying 6 reaction wheels instead of 3 is a ~100K + . So redundancy to increase lifetime on orbit is not that expensive.

Flight Computing

- While the raw data rate for NEO Synthetic Tracking is ~50-100X smaller than for Earth orbiting satellites. It is still way too large to send to the ground.
- We need ~0.5 teraflops of computing in space.
- The TESS mission flew a VIRTEX-7 FPGA (peak 4.5 trillion arithmetic ops/sec)
  - We did a “feasibility test” programming the multi-vector shift/add on a VIRTEX-7 (evaluation board) using < 10% of resources of the VIRTEX-7
- The small company that built the flight camera electronics for the TESS mission is now putting Xilnex ultra-scale FPGAs into their flight products.
  - Generation after Virtex-7. They also sell a V-7 board that uses ~40W.
- Another alternative is redundant computing with GPUs. FPGA are significantly more radiation tolerant then GPUs. But GPUs are much easier to program. In addition, many GPU/space enthusiasts have suggested redundant computing.
  - Do the computation twice, if they differ redo a 3rd time.

Thermal IR MicroSats (in follow up mode) very rough numbers

- A telescope like Pan-STARRS (4 image tracklet) spend ~180 sec/FOV. In 10 hrs it is looking at 200 FOV and on average finding 3 NEOs/night (i.e., ~1,000/yr)
- A thermal IR telescope would only observe those 3 NEOs. (Trade aperture for integration time, perhaps with synthetic tracking; increase T by ~66, reduce telescope dia by **~2.8 X** reduction in telescope **dia** Integration Time~ D^{-4})
- In addition, the follow up telescope does not need a huge FOV.
  - Smaller focal plane (1 Mpix?)
  - Higher sensitivity by Nyquist sampling the diff limited PSF
    - The area*solid_angle produce of zodi background ~ λ^2
    - Perhaps ~20% reduction in require telescope diameter
- Is it then possible to cut the size of the thermal IR satellite to fit inside of an ESPA class spacecraft. (Maybe, is this worth a serious look?) Reduce the cost enough to afford a constellation of IR MicroSats?

Summary

- Synthetic Tracking is a powerful technique that allows small telescopes to detect faint objects, otherwise requiring a much larger (and expensive) telescopes
  - In 2019-20, the technique will be deployed across a global network of telescopes to monitor Earth-orbiting objects.
- Cubesat and CMOS detector technologies have had made major advances in the past few years in the commercial sector:
  - Cubesat components are now used in Microsats (up to 250 kg).
  - Components are mass produced (100's/yr) at low cost with 100's of years of flight testing by 100's of Cubesats on orbit.
- A constellation of 5 Microsats avoids "saturation", reaching ~90% complete in 2.7 yrs. In 5 yrs ~89% of H<22 mag NEOs will have 10 or more observations (with 0.1 arcsec astrometry), potentially leading to accurate orbits for those NEOs.
- While the ultra-low cost Microsat technology can not be applied to a full sized thermal IR "NEO Search" mission:
  - It may be possible for a thermal IR follow-up mission that may be used to measure diameters of already discovered NEOs.